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Operational Behavior of a Solar-Fed Bidirectional Substation for 4GDH Networks

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Abstract

Decentralized feed-in of solar surplus heat from prosumers into a District Heating Network is here addressed. A specified architecture combining a Return/Supply connection, a set of valves, a feed-in pump and a primary side connection of the solar field led to the conception and fabrication of a bidirectional substation prototype. The latter is tested in a hardware-in-the-loop configuration regarding the consumer and solar field sides while the DHN side of the substation prototype is connected to a real DHN. A 12-days sequence, representative of typical days, with varying solar irradiation, DHN thermo-hydraulic conditions and consumer demands is performed with the prototype. A set of indicators showed i) an inappropriate behavior of the controller during the coldest days, ii) various improvements of the solar fraction during the hottest days (with up to 52% of total solar fraction) and iii) rather good performances of the controller (about 90% effectiveness). The analysis was completed by the observation of detailed dynamic result for one day. Different operating regimes (full DHN consumption, solar self-consumption complemented by the DHN, solar self-consumption and feed-in) could be observed during a single day highlighting the modularity of the BSST to switch automatically (by hydraulic balancing) from one mode to the other.

Keywords: Solar Feed-In, Decentralized, Bidirectional Substation, District Heating,

1. Introduction and State-Of-the-Art

In the “2way District Heating” course of action from the 4th Generation District Heating concept (Lund et al., 2014), decentralized feed-in of solar heat from prosumers seems to be a promising solution to increase the share of renewable energy in District Heating Networks (DHN), especially in dense urban areas with limited ground surface and high cost of land. However, when scattered customers roofs are used to collect and inject heat locally in a network, a new component is required. Such a component, referred here as Bidirectional SubStation (BSST), must be able to transfer heat i) from the DHN to the local consumer when the locally produced solar heat is not sufficient and ii) from the local consumer to the DHN when solar heat is in excess.

Among the various reinjection principles, Return to Supply (R/S) feed-in is chosen since it seems to be the most flexible option from the DHN point of view (Lennermo and Lauenburg, 2016). Indeed, it allows a reasonably low temperature in the solar field (better panels' efficiency) without increasing the return line temperature (better efficiency of other heat generators and lower heat loss) while presenting lower risks in terms of pipe fatigue. However, R/S feed-in implies the necessity to cope with the variable i) local differential pressure between the return and supply lines, ii) solar irradiation, and iii) local DHN return temperature. Moreover, the feed-in temperature must be close to the local supply line temperature of the network to prevent both pipe fatigue (Lennermo et al., 2019) and unmet customer demand.

While architecture and operational behavior of feed-only substations are addressed in the literature rather extensively (Lennermo et al., 2019; Rosemann et al., 2018; Schäfer and Schmidt, 2016), 2-way substations studies are seldom in the open literature. Though, the combined substation concept of Rosemann et al. (2017) can be noted. Starting from usual feed-only architecture combining a set-of-valves and a feed-in pump on the primary side, they used a rather complex control algorithm and architecture of the substation combining on the secondary side the solar field together with consumer internal heating loops.

In the frame of the Horizon 2020 THERMOSS project, specifications, modeling and prototype testing of a 2-way substation with the solar field connected on the primary side is performed. While the specifications and modeling approach were presented respectively in Lamaison et al. (2017) and Lamaison et al. (2018), the present paper deals with the design and original test approach of a BSST prototype combining hardware-in-the-loop and real experimental DHN.

2. Architecture and Control

2.1. Architecture

To build the BSST architecture, an initial review on two-way substation both from the industrial and research point of view led to the fact that i) nothing exists in the catalogue of usual manufacturers; ii) the Return/Supply (R/S) type of feed-in is the most promising compared to other types (R/R or S/S).

Discussions with DHN operator and substation manufacturer led to specifications in the form of constraints and requirements, insisting specifically on modularity and cost. Different features (local usage, network connection and control strategy) were then combined to propose various architectures. After pros and cons listing, solutions involving complete reinjection of the heat into the DHN seemed the most promising (Lamaison et al., 2017), leading to the technical drawing shown in Fig. 1. Especially, the substation does not include a storage as usually associated to a solar field. Indeed, thanks to the presence of the DHN as heat sink and because of the extra heat loss induced by a storage, it is not necessary and thus preferred not to include a storage in the architecture

In Fig. 1, connections to the supply and return lines of the DHN are schematically represented on the left block. Regarding the right block, it represents the consumer and exhibits a separation of space heating (SH) and domestic hot water (DHW) supplies at the primary side (dedicated heat exchangers) Regarding the middle block, it is comprised of the connection to the solar loop and the entire feed-in loop components. For the latter, the main components are the feed-in pump (P_SST_FEED), the heat exchanger (ECH_BESST_SOL) and the feed-in valve (V_BSST_FEED). Red and blue lines respectively indicate hot and cold lines. Red, blue, orange and black labels respectively denote temperature probes, pressure probes, mass flow meters and equipment. The main equipment (pumps, heat exchangers and valves), small hydraulic components (filters, check valves) and the instrumentations are highlighted. Also, it is important to mention that drains (all loops), safety valves (all loops) and expansion tanks (solar and SH loops) are not shown.

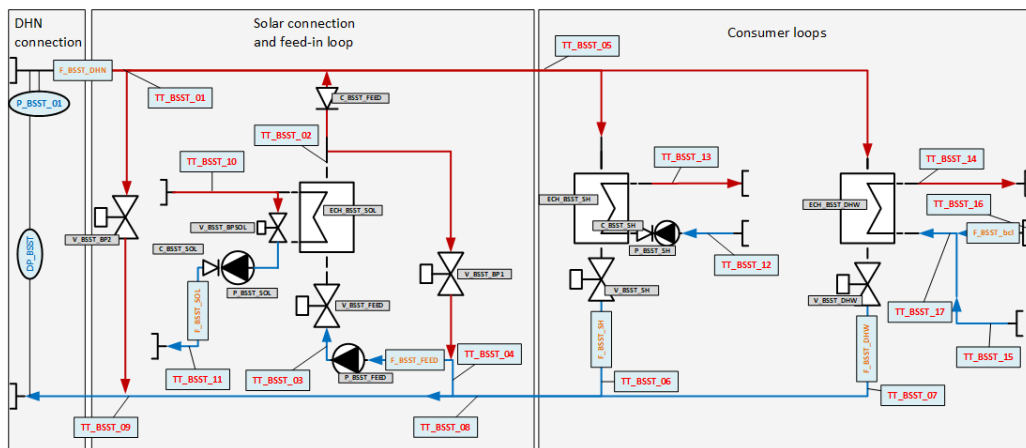


Fig. 1: Technical drawing of the BSST prototype

2.2. Main principles and control

The two main operating modes of the substation are schematically represented in Fig. 2:

- In mode 1, the heat consumption for domestic hot water and space heating is larger than the solar production. The solar energy if any is used for the consumer needs in addition to the heat coming from the network. The flow in the service lines is thus from the supply to the return line;

- In mode 2, the heat consumption is lower than the solar production. The solar energy is used to entirely satisfy the consumer needs if any and the surplus heat is reinjected to the network. The flow in the service lines is thus from the return to the supply line.

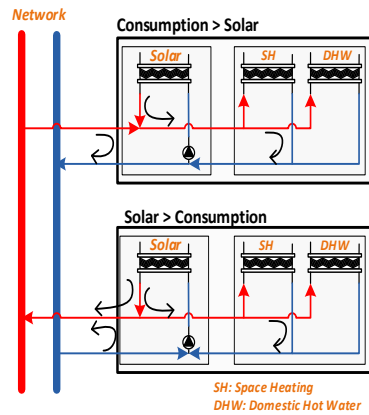


Fig. 2: Main operating principles

Regarding the substation control, the solar field pump (P_BSST_SOL) is controlled to obtain a given flow rate set point. Similarly to Lennermo et al. (2019), the latter is calculated using a cascaded combination of a theoretical solar field model (function of solar irradiation, return temperature TT_BSST_11 and ambient temperature) and a closed-loop PID leading to a desired set point for the outlet solar field temperature (TT_BSST_10). For the latter set point, an adapted heating law as a function of the ambient temperature is implemented. The feed-in pump (P_BSST_FEED) is controlled to have the same flow-rate as in the solar loop (accounting for the calorific value correction between the glycol on the solar loop and the water in the BSST loop). The extra set of valves (V_BSST_BP1 and V_BSST_BP2) are used for specific transient conditions. Based on the demand side and solar production, the flow rate will automatically be distributed, due to hydraulic balancing, such as in mode 1 or mode 2.

3. Sizing, test setup and procedure

3.1 Sizing

Following a stage of modeling (Lamaison et al., 2018), the substation has been sized (heat exchangers, valves and pumps) for 42 kW in SH, 60kW in DHW and 70kW in solar. According to the sizing and architecture, the substation has been assembled as shown in Fig. 3.

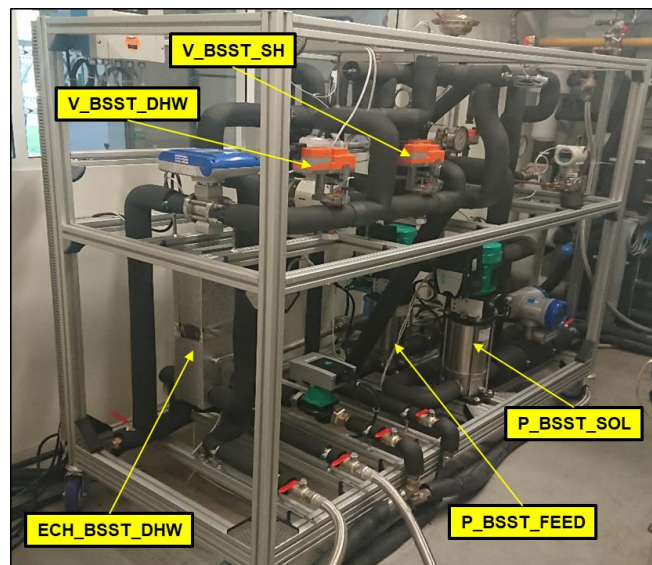


Fig. 3: Picture of the bidirectional substation with some components of Fig. 1 highlighted

3.2 Testing setup and procedure

In the frame of the project, different types of tests were performed:

- **Unitary tests:** Validation of the functional control of the different blocks;
- **Real weather conditions:** Operation of the substation with a real solar field;
- **Real time emulated weather conditions:** Operation of the substation in a broader range of operating conditions but with an emulated solar field.

For the present work, only the emulated weather conditions tests are presented. For those tests, a dynamic whole system methodology, called SCSPT (Short Cycle System Performance Test) and adapted from Albaric et al. (2008), is used. As shown in Fig. 4, it consists in real-time hardware in the loop (HIL) dynamic system test for thermal systems during 12 days. It relies on TRNSYS dynamic simulation system to cover the typical working conditions during 12 months of operation. The simulation calculates real time needs (building) and production (solar field). These are then sent to a Labview program, which sent the required info to various thermo-hydraulic modules, composed of heat exchangers, valves, pumps and electrical resistances, which translate the theoretical needs in real thermo-hydraulic fluxes. The test conditions are here representative of annual variations of the Zurich climate (CH).

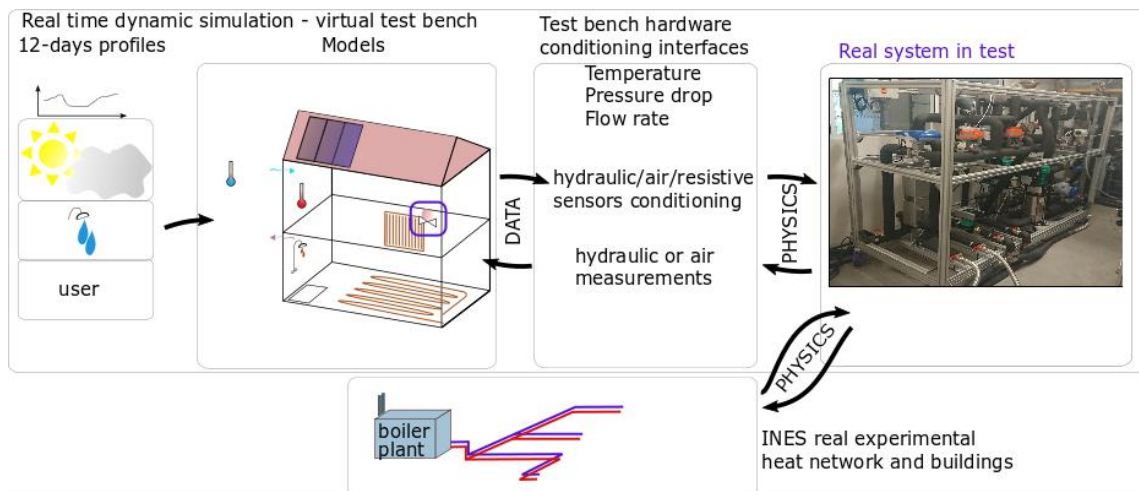


Fig. 4: Dynamic whole system test methodology

The entire setup for testing the substation is finally as shown in Fig. 5 with the BSST prototype surrounded by different components.

- **The emulated building space heating (SH):** The building model is a typical 4 levels building erected in the early 2000's in France, parallelepiped U-shape, convex side facing south. It is composed of 12 apartments, each heated according to its thermal zone temperature by local radiator flow rate adjustment with thermostatic valve. The space heating flow is a constant value (local bypass at radiator level when thermostatic valve adjust the flow rate in radiator).
- **The emulated building domestic hot water (DHW) and sanitary loop:** The DHW model consists in a repeated daily pattern draw-offs profile for 12 households (obtained using Jordan and Vajen, 2005), with total daily consumption variation from month to month. The DHW sanitary loop demand is not calculated from simulation but rather physically emulated. To do so, a specific hydraulic module for real heat dissipation to ambient temperature was built. The water flow rate in the loop is fixed to 300kg/h by recycling pump and the heat dissipation is controlled dynamically to keep the inlet-outlet temperature drop close to 5K.
- **The emulated solar field:** The modeled solar field is facing south and is composed of 50 m² of common technology flat solar panel. It is worth mentioning here that the size of this solar field is limited by the capacity of the hardware-in-the-loop setup. In theory and as discussed in Lamaison et al. (2018), the size of the solar field can be larger when associated to such substation.
- **The real DHN:** Unlike the building and solar field sides that are emulated, the DHN side is connected

to a small real DHN with varying local differential pressure and return temperature conditions. It is composed of a district heating network of about 200m length, supplying heat to real buildings and to an emulated building (the one in which the BSST is connected). The main production units of this DHN are a condensing gas boiler of 280kW, a heat pump of 50kW and a solar field of 300m². The network is also equipped with a hot storage tank of 40m³.

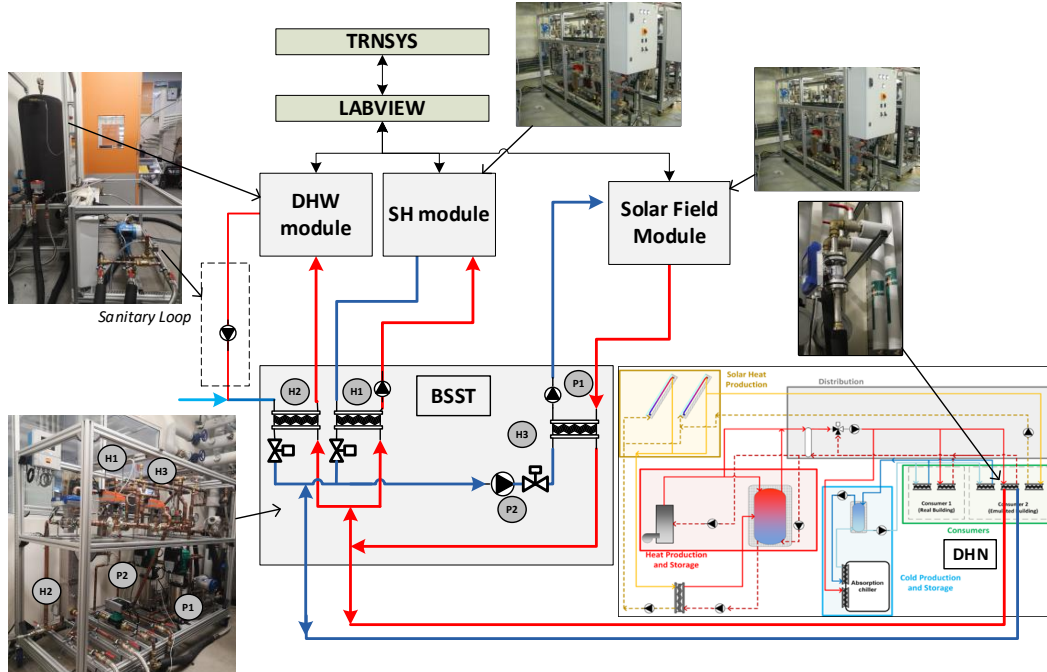


Fig. 5: BSST test setup at CEA-INES: emulated building, emulated solar field and real DHN

4. Results and discussion

The results are firstly presented globally for each day of the test sequence using indicators and secondly with the analysis of the dynamic behavior for a specific day of operation.

4.1. Indicators definition and results for the 12-days sequence

Using the nomenclature of both Fig. 1 and Fig. 6, Tab. 1 and Tab. 2 respectively present the definition of a set of energy-based and control-based indicators. While the former objective is to illustrate the energetic performances of the substation, the latter one is to present the controller performances in feed-in mode.

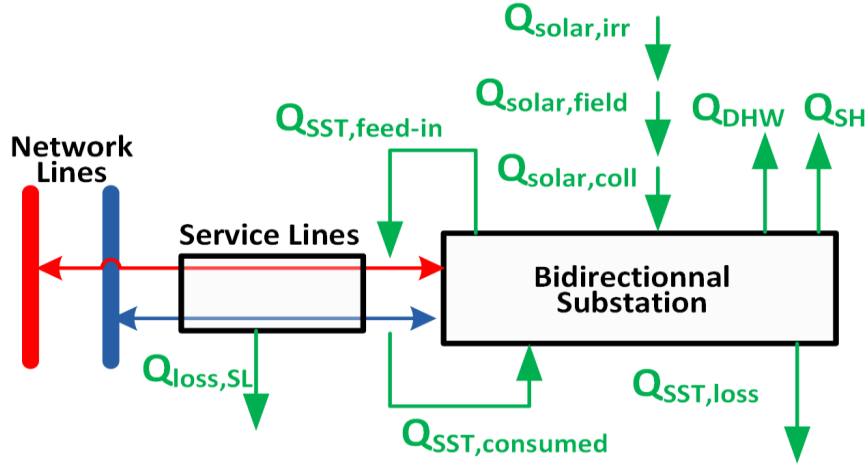


Fig. 6: Schematic representation and nomenclature associated to thermal power fluxes (Q) around the substation

Tab. 1: Energy (E) based indicators definition

Name	Definition	Description
Solar Field Efficiency	$\eta_{SF} = \frac{E_{solar,field}}{E_{solar,irr}}$	Collected energy at the panels level divided by global irradiation on the solar panels plan
Solar Plant Efficiency	$\eta_{SP} = \frac{E_{solar,coll}}{E_{solar,irr}}$	Collected energy at the solar heat exchanger divided by global irradiation on the solar panels plan
Substation Efficiency	$\eta_{th} = \frac{E_{SST,feed-in} + E_{SH} + E_{DHW}}{E_{solar,coll} + E_{SST,cons}}$	Total distributed energy by the SST divided by total collected energy by the SST
Solar Fraction	$SF = \frac{E_{SH} + E_{DHW} - E_{SST,cons}}{E_{SH} + E_{DHW}}$	Solar energy self-consumption by building divided by total building consumption
Total Solar Fraction	$SF_{tot} = \frac{E_{SST,feed-in} + E_{SH} + E_{DHW} - E_{SST,cons}}{E_{SH} + E_{DHW}}$	Solar energy self-consumption and reinjection divided by total building consumption
Solar Ressource Feed-in Rate	$\tau_{feed} = \frac{E_{SST,feed-in}}{E_{solar,coll}}$	Feed-in energy divided by collected energy at the solar heat exchanger
Substation Prosumer Rate	$\tau_{pro} = \frac{E_{SST,feed-in}}{E_{SST,cons} + E_{SST,feed-in}}$	Feed-in energy divided by the summed fluxes at the entrance of the SST on the DHN side
Substation Prosumer Rate with respect to DHN	$\tau_{pro,DHN} = \frac{E_{SST,feed-in}}{E_{SST,DHN} + E_{SST,feed-in}}$	Locally feed-in energy divided by summed fluxes at the entrance of all the SST of the entire DHN

Tab. 2: Control-based indicators definition

Name	Definition	Description
Standard Deviation of the Feed-in Temperature	$\sigma_{feed-in} = \sqrt{\frac{\sum (TT01 - T_{TT01,mean})^2}{N_{points}} \Big _{F_{BSST,DHN} < 0}}$	When reinjection occurs, standard deviation of the hot line temperature with respect to the reinjection setpoint
Feed-In effectiveness at 2K	$\varepsilon_{feed-in,E,2K} = \frac{\sum P_{feed,in} \cdot \Delta t \Big _{F_{BSST,DHN} < 0 \ \& \ TT01 > T_{sp,TT01} - 2K}}{\sum P_{feed,in} \cdot \Delta t \Big _{F_{BSST,DHN} < 0}}$	When reinjection occurs, energy-based integral when setpoint is satisfied within a 2K margin divided by the total energy-based integral

With the indicators described beforehand, Tab. 3 now presents those for the 12-days sequence of our testing procedure, as described in Section 3. The main conclusions to draw from this Table are the following:

- During the 6 colder days, the solar field does not produce. This is explained by the too high outlet solar field set point constrained by the reinjection arrangement. Indeed, the controller setpoint calculation is based on the assumption that reinjection may occur and is thus rather high because the network operates at high temperature (an average of 75°C for these 6 days). The latter combined with the low irradiation and the low temperature in the solar loop piping (because of the low ambient temperature) leads to an inappropriate solar field operation.
- During the 6 days for which solar reinjection takes place, we observe various levels of solar fraction but more striking various level of total solar fraction. The latter is due to the increased gap for hotter days between the local demand of the building and the energy produced by the solar field. It is worth noting here that the largest value of total solar fraction of 52.0% is still not that high. The reason is the rather small aperture area of the emulated solar field because of test bench limitations (see Section 3). Additional tests not shown here were performed with real solar field of 70kW and solar fractions up to 80% were reached.
- Regarding the performances of the controller, the standard deviation of the feed-in temperature is rather high compared to what was expected from previous tests with a real solar field (see Section 3), for which values around 1.5°C were obtained. These results are explained by the fact that the controller parameters were calibrated with this real solar field and not refreshed after the switch to an emulated solar field (with lower aperture area and less inertia). However, the feed-in effectiveness exhibits reasonably good values (average of 92%) highlighting the fact that reinjection on the network occurs at an appropriate level of temperature.

Tab. 3: Indicators for the 12-days test sequence

Day	η_{SF}	η_{SP}	η_{th}	SF	SF _{tot}	τ_{feed}	τ_{pro}	$\tau_{pro,DHN}$	$\sigma_{feed-in}$	$\epsilon_{feed-in,E,2K}$
1	0	0	98.2	0	0	0	0	0	-	-
2	0	0	98.3	0	0	0	0	0	-	-
3	0	0	98.4	0	0	0	0	0	-	-
4	21.4	20.5	98.6	4.3	4.7	6.0	0.4	0.1	5.6	91.7
5	18.4	17.6	98.8	4.8	6.0	16.2	1.21	0.3	5.8	85.0
6	34.8	33.4	99.7	18.7	25.5	26.3	7.7	2.5	4.0	98.7
7	35.8	34.3	99.6	20.1	33.4	39.3	14.3	1.9	4.0	92.1
8	36.0	34.6	99.9	14.9	52.0	71.1	30.4	4.0	3.7	90.5
9	33.1	31.7	99.4	11.9	32.8	62.1	19.1	2.9	4.1	96.3
10	0	0	97.6	0	0	0	0	0	-	-
11	0	0	98.2	0	0	0	0	0	-	-
12	0	0	98.3	0	0	0	0	0	-	-

4.3. Focus on dynamic results for a specific day

In the present section, we observe the detailed dynamic results for day n°6 of the sequence with the indicators results being highlighted in Tab. 3.

Fig. 7 presents thus results obtained for day n°6 of the sequence between 9a.m. and 7p.m. in terms of various heat transfer rates and temperatures. Fig. 8 presents additional results for the same observation period in terms of heat power at DHN level, controller actuators signals and differential pressures.

Focusing on regions A, B and C highlighted in the Figure, we observe the following operating regimes:

- **Region A:** The BSST is in consumption mode from the DHN point of view (mode 1 in Fig. 2). The outlet solar loop temperature and thus the outlet feed-in loop temperatures are below the feed-in set point. The feed-in pump is off and the solar pump operates at its lowest speed. The building consumption is thus entirely met by the DH and TT01 at the entrance of the substation on the hot service line is representative of the DHN local supply pipe temperature. The local differential pressure, here imposed by the DHN pump, is following the local building consumption indicating that i) there is no local consumption of solar heat, and ii) the other consumer on the network have a rather constant heat consumption (see top graph of Fig. 7).

- Region B:** The BSST is in consumption mode from the DHN point of view (mode 1 in Fig. 2). However, periodically, the SST consumption is lower than the building consumption indicating solar heat production and self-consumption. This is the case especially at the end of the period where the outlet solar field temperature surpasses the feed-in set point. This self-consumption is achieved in a period where the substation consumption is significantly varying because of DHW draw-offs (see DHW valve opening in Fig. 8). The latter variations together with the variable solar fraction lead to large variations of the local differential pressure drop (imposed by the DHN pump) indicating strong flow rate variations in the DHN.
- Region C:** The substation is in feed-in mode from the DHN point of view (mode 2 in Fig. 2). The solar heat being used for both the local building heat demand and for reinjection into the DHN. The feed-in pump is ON and the valve V_BSST_FEED together with the pump speed are adjusted to match the flow rate set point. TT09 at the entrance of the substation on the cold service line is representative of the DHN local return pipe temperature. Because of feed-in mode operation, the differential pressure is here imposed by the feed-in pump. Its variations are following the variations in demand of the other DHN consumers (see top graph on Fig. 7).

The main negative observation that can be made here for this day of operation is the low frequency periodic alternation between consumption and feed-in modes even though solar irradiation and building consumption do not exhibit such behaviors. The latter is attributed to controller setting slightly inappropriate since they were established during tests with a real solar field (with larger aperture area and more inertia) and not refreshed for this new testing setup.

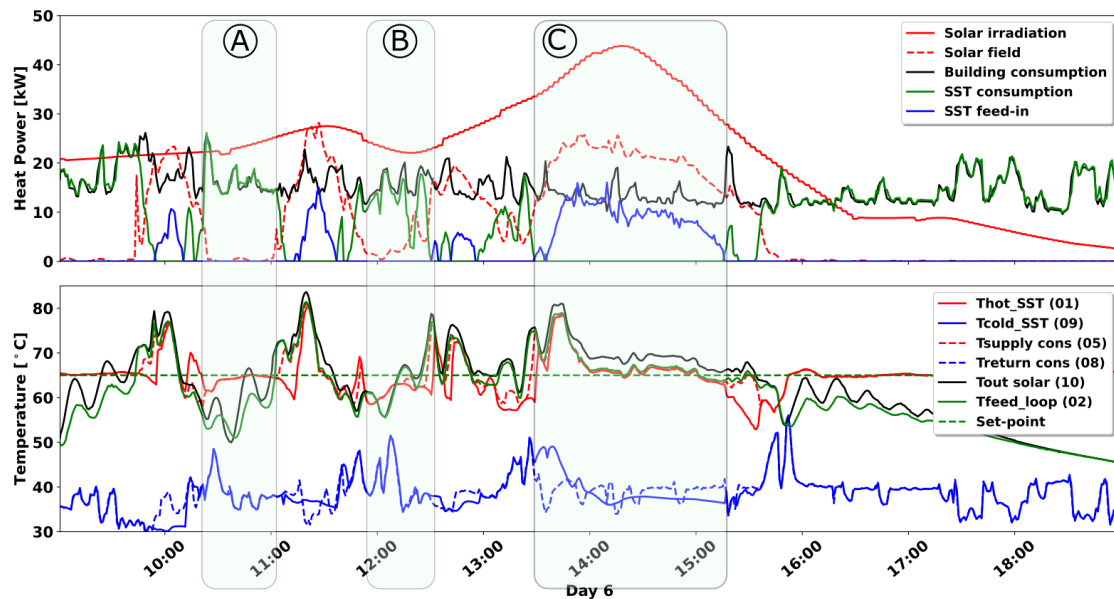


Fig. 7: Experimental results obtained for day 6 of the sequence (Top: heat power; Bottom: Temperatures)

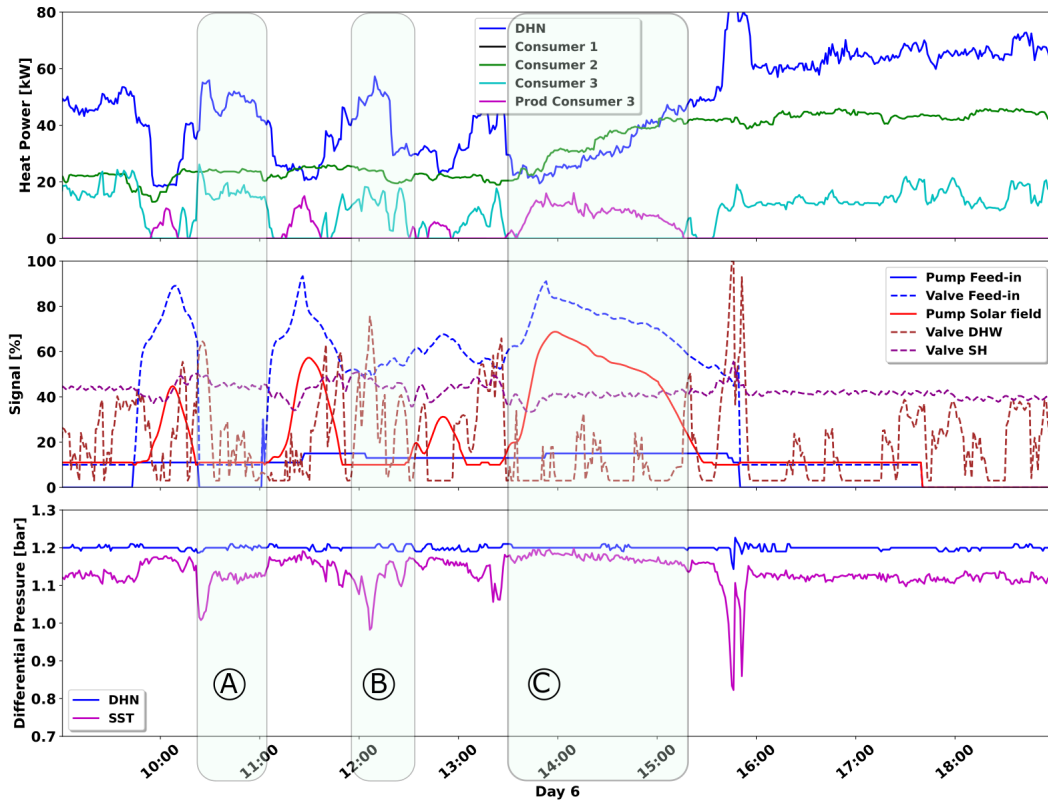


Fig. 8: Experimental results obtained for day 6 of the sequence (Top: heat power at DHN level; Middle: Controller actuators, Bottom: Differential Pressure)

A very interesting insight offered by our testing setup is the observation of the DHN pressure field variations because of the reinjection. Indeed, because of the usage of a real network, furthermore linear, influence on the DHN pressure cone is directly visible. As shown in Fig. 9, which presents a qualitative explanation of the influence of the feed-in on the real DHN pressure cone, the solar heat produced at prosumer 1 benefits both the local consumer (consumer 3 = prosumer 1, cf. top graph on Fig. 7) and consumer 2, which thus reduces its dependence to the main production plant.

It is worth mentioning here that during tests with extreme conditions (larger solar field, low demand on the network), we reached situations with a fully inverted pressure cone which becomes problematic if no bypass for backflow is installed in the main plant (as mentioned in Heymann and Rühling, 2016).

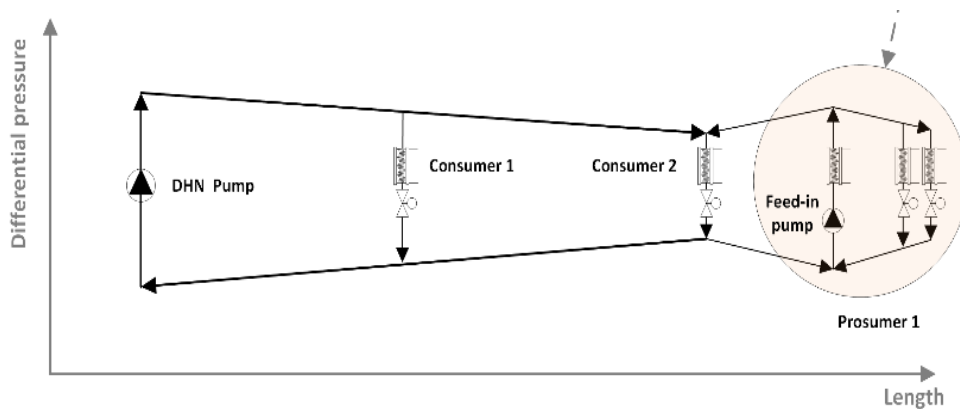


Fig. 9: Qualitative impact of the BSST on the real DHN pressure cone

5. Conclusion

The present paper presented the operational behavior of a new prototype of a solar-fed bidirectional substation. This represents the final step of the THERMOSS project in which specifications, modeling, sizing, manufacturing and testing of such a prototype was performed. The prototype was sized for about 100kW in consumption and 70kW in production and can be considered in a first approach as a superposition of a consumption substation (with primary separation between DHW and SH) and a solar-fed feed-in substation.

The testing setup was composed of i) an emulated building SH and DHW consumption (real-time TRNSYS simulation associated to a Labview program and a set of thermo-hydraulic modules), ii) an emulated solar field (real-time TRNSYS simulation associated to a Labview program and a thermo-hydraulic module), and iii) a real 200m long linear DHN. The testing was performed during 12 days representative in terms of boundary conditions of the 12 months of the year.

A set of indicators showed i) an inappropriate behavior of the controller during the coldest days, ii) various improvements of the solar fraction during the hottest days (with up to 52% of total solar fraction) and iii) rather good performances of the controller. The analysis was complemented by the observation of detailed dynamic result for one day of the sequence. Different operating regimes (full DHN consumption, solar self-consumption complemented by the DHN, solar self-consumption and feed-in) could be observed during a single day highlighting the modularity of the BSST to switch automatically (by hydraulic balancing) from one mode to the other. Unwanted low frequency oscillations between the modes were also observed.

As a conclusion, we can say that the experimental results shown here represent a satisfactory first step for such a bidirectional substation. However, there exists still some room for improvements regarding the control, especially by benefiting from the local consumer information to adapt the control of the feed-in loop. This is currently under investigation.

6. Acknowledgments

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